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Rapid Communication

First discovery of Holocene Alaskan and Icelandic tephra in Polish peatlands

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ABSTRACT: Despite the discovery of cryptotephra layers in over 100 peatlands across northern Europe, Holocene cryptotephra layers have not previously been reported from Polish peatlands. Here we present the first Holocene tephra findings from two peatlands in northern Poland. At Bagno Kusowo peatland we identify the most easterly occurrence of the AD 860 B tephra, recently correlated to the White River Ash (WRAe) derived from Mount Churchill, Alaska. A shorter core from Linje peatland contains tephra from the Askja 1875 eruption, extending the spatial distribution and regional importance of this Icelandic tephra in Eastern Europe. Our research indicates the potential of cryptotephra layers to date and correlate the growing number of palaeoenvironmental studies being conducted on Polish peatlands and contributes towards the development of a regional Holocene tephrostratigraphy for Poland. Copyright © 2017 The Authors. *Journal of Quaternary Science* Published by John Wiley & Sons, Ltd.

KEYWORDS: Askja; cryptotephra; Eastern Europe; Mount Churchill.

Introduction

Microscopic layers of volcanic ash, 'cryptotephras' have been identified in over 100 peatlands in Northern Europe (e.g. van den Bogaard and Schmincke, 2002; Dugmore *et al.*, 1995; see summary in Lawson *et al.*, 2012). The individual shards which constitute cryptotephra layers can be extracted and geochemically analysed. When combined with stratigraphic information, the analysis of glass shard geochemistry can allow for the assignment of a cryptotephra layer to a given volcano or eruption. Well-dated cryptotephra layers provide valuable isochrons for the dating and correlation of palaeoenvironmental research (e.g. Lowe, 2011).

Intact peatlands provide ideal archives for the examination of environmental change and human influence over the Holocene. Polish peatlands are increasingly being exploited for their palaeoenvironmental records, which span much of the Holocene and have the potential to provide high-resolution records of both climatic change and human influence (Lamentowicz *et al.*, 2015a; Marcisz *et al.*, 2015; Kajukało *et al.*, 2016; Gałka *et al.*, 2017). Furthermore, Polish peatlands span important environmental gradients providing opportunities to bridge the gap between records in Western Europe (influenced strongly by oceanic climate) and those in Boreal Russia (Lamentowicz *et al.*, 2015b).

Despite the discovery of cryptotephra layers in multiple sites across northern Europe (Lawson *et al.*, 2012), and a report of the Lateglacial Laacher See tephra (of German origin) in lake sediments underlying peat in north-west Poland (Juvigné *et al.*, 1995), no tephra layers have previously been reported from Polish peatlands. The discoveries of multiple tephra layers of Icelandic origin (Hässeldalen, Askja-S, Askja 1875 and two unknown potential Icelandic tephras) in Lake Czechowskie (northern Poland) (Ott *et al.*, 2016; Wulf *et al.*, 2016), and the Askja 1875 tephra in Lake Żabińskie, north-east Poland (Tylmann *et al.*, 2016), indicate that tephra fell out over Poland during the Lateglacial and Holocene and may also be present in peatlands. The recent identification of tephra shards with a geochemistry compatible with the Askja volcanic system in sand deposits dated to 2.3 ± 0.1 ka BP (Housley *et al.*, 2014) provides further evidence for the long-distance transport of Icelandic tephras towards Poland. Cryptotephra layers could provide valuable chronological markers allowing for the correlation of palaeoenvironmental reconstructions across multiple sites both within and beyond Poland. Tephra layers which correspond to environmental or human events may be particularly valuable (Stivrins *et al.*, 2016). The aim of this study is to evaluate whether historical cryptotephra layers are preserved in peatlands in north-central Poland and therewith to add to the tephrostratigraphy for this region.

Study sites and methods

Linje mire

Linje mire is a poor fen located near Bydgoszcz city, in northern Poland (53°11′N, 18°18′E) (Fig. 1). A 2.5-m core was extracted

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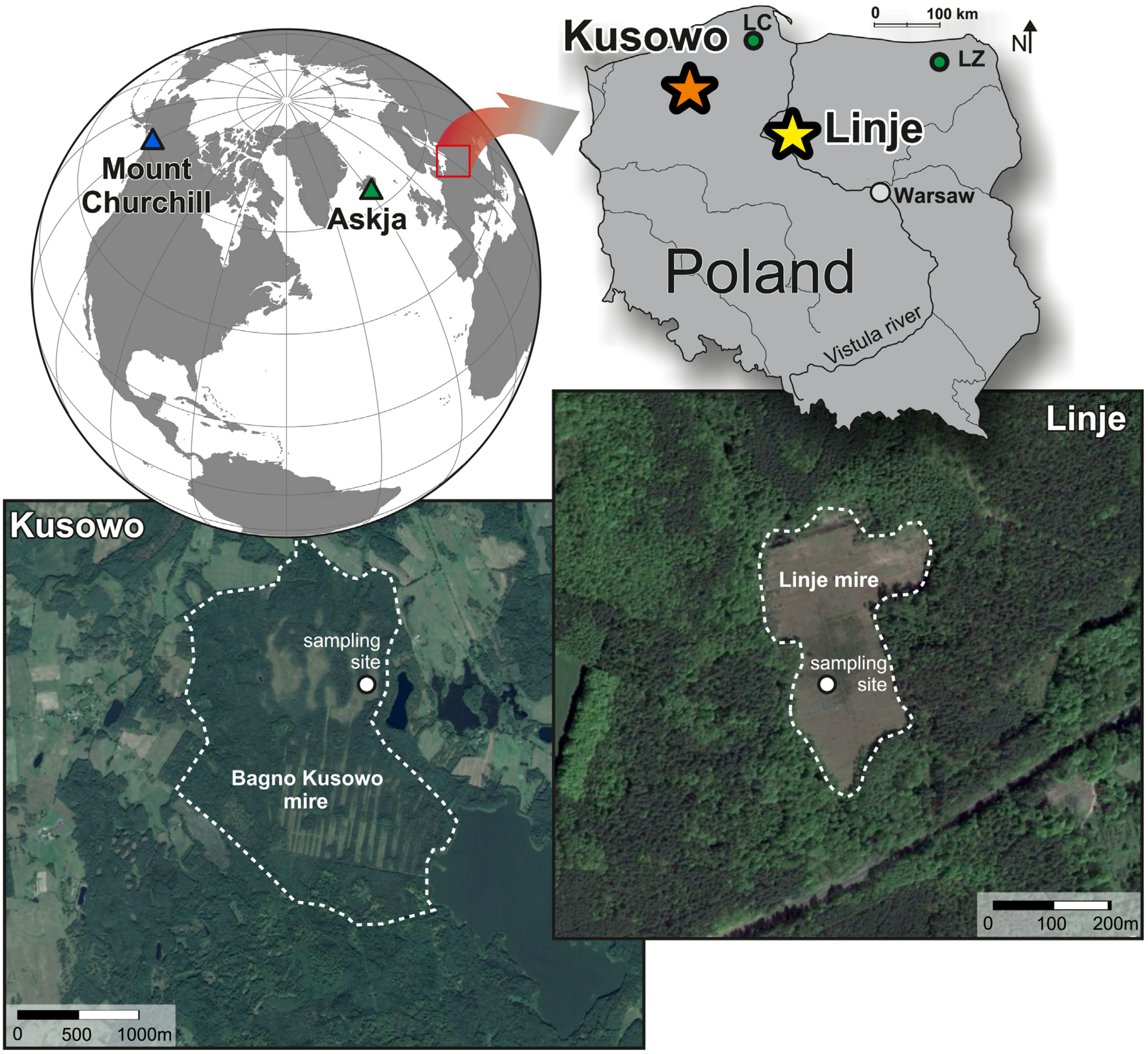

Figure 1. The location of Linje and Bagno Kusowo peatlands within Northern Poland. Globe indicates the location of the source volcanoes for tephras identified in this study, Mount Churchill in Alaska, and the Askja volcano in Iceland. The locations of sites mentioned in the text are included as follows: Lake Czechowskie (LC) and Lake Żabińskie (LZ).

from the central part of the mire (Marcisz *et al*., 2015). The peatland is located at 91 m a.s.l. and lies along the border of oceanic and continental air masses, with mean annual precipitation of 500–550 mm (Hałas *et al*., 2008). The vegetation on Linje mire indicates a poor fen, but areas of ombrotrophic vegetation are present in the centre of the site (Kucharski and Kloss, 2005).

Bagno Kusowo

Bagno Kusowo (Kusowo) is a Baltic bog in northern Poland (53°48′N, 16°35′E). A core of 8 m, thought to coincide with the deepest peat at the site, was extracted (Lamentowicz *et al*., 2015a). The altitude of the site averages between 150 and 160 m a.s.l. (Gałka *et al*., 2017). Kusowo is influenced much more by the oceanic climate than Linje. Total annual precipitation is in the region of 650 mm.

Methods

A peat monolith was sampled from Linje mire using a Wardenaar sampler (Wardenaar, 1987), while a long core from Kusowo was extracted with a 1-m-long, 8-cm-diameter INSTORF corer. Continuous samples (increments of 1 cm at Linje and 10 cm at Kusowo) were ashed at 550 °C, washed with 10% HCl, mounted onto slides and examined at a magnification of 200× (Pilcher and Hall, 1992; Swindles *et al*., 2010). Where tephra shards were recognized, new samples were extracted for geochemical analysis. Extraction for geochemical analysis followed the acid digestion method (Dugmore *et al*., 1992). Samples were treated with hot concentrated HNO_3 and H_2SO_4 acids, diluted with water and sieved at 10 µm. The coarse residue was rinsed thoroughly with clean water. Recent work has shown that tephra shards extracted using the acid digestion method and then analysed using electron probe microanalysis (EPMA) are geochemically indistinguishable from shards extracted using density separation (Roland *et al*., 2015; Watson *et al*., 2016).

Samples were mounted onto glass slides using EpoThin resin (Dugmore *et al*., 1992) and polished to a 0.25-µm finish. EPMA was conducted on a Cameca SX100 at the University of Edinburgh. All analyses were conducted with a

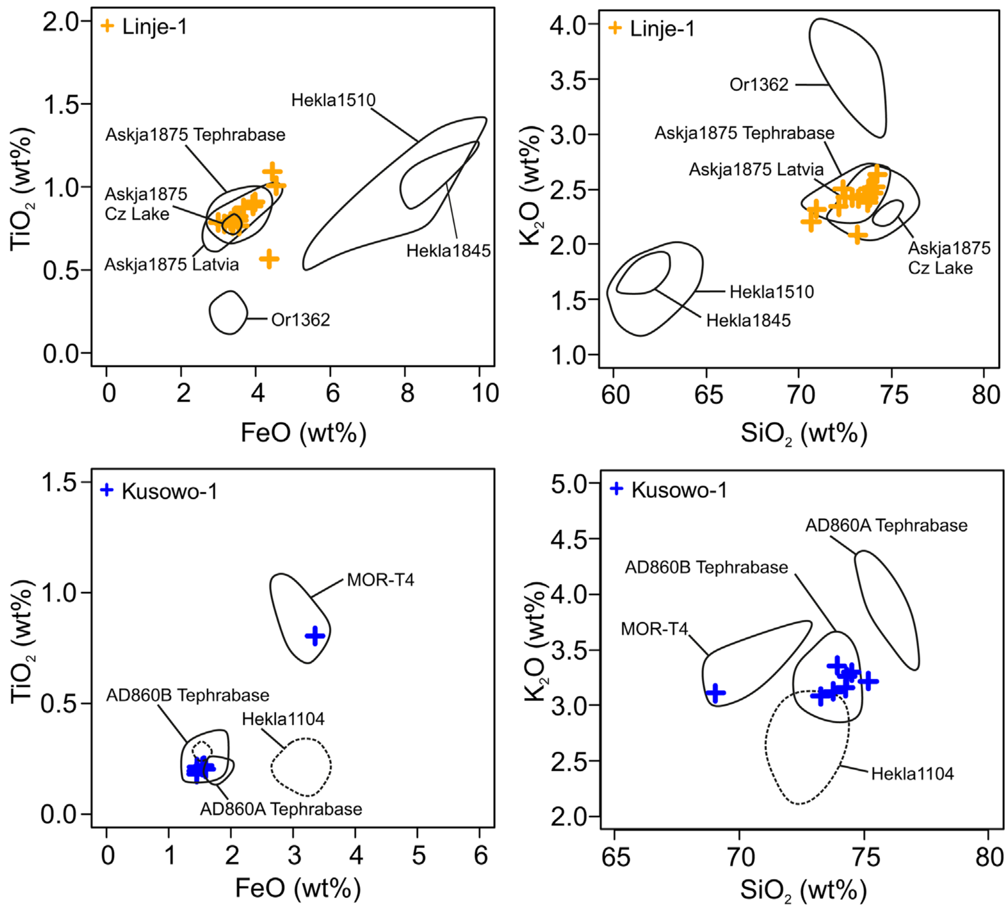

Figure 2. Major element bi-plots indicating the geochemistry of glass shards from Bagno Kusowo and Linje peatlands. Reference data: AD 860 A: Pilcher *et al.* (1995), Swindles (2006); AD 860 B: Hall and Pilcher (2002), Swindles (2006); Askja 1875: Larsen *et al.* (1999), Oldfield *et al.* (1997), Pilcher *et al.* (2005); Askja 1875 Latvia: Stivrins *et al.* (2016); Askja 1875 Czechowskie Lake: Wulf *et al.* (2016); Hekla 1845: Watson *et al.* (2015); Hekla 1510: Dugmore *et al.* (1995), Larsen *et al.* (1999), Pilcher *et al.* (1996), Swindles (2006); Hekla 1104: Pilcher *et al.* (2005), Pilcher *et al.* (1996), Streeter and Dugmore (2014); MOR-T4: Chambers *et al.* (2004). Öræfajökull (Or) 1362: Hall and Pilcher (2002), Larsen *et al.* (1999), Pilcher *et al.* (2005), Pilcher *et al.* (1995).

beam diameter of 5 μm, 15 kV and beam currents of 2 nA (Na, Mg, Al, Si, K, Ca, Fe) or 80 nA (P, Ti, Mn) (Hayward, 2012). Secondary glass standards, rhyolite (Lipari) and basalt (BCR-2G) were analysed before and after EPMA runs of unknown glass shard analyses. Raw EPMA data are supplied in the Supplementary Information, Table S1.

Two radiocarbon dates were obtained on above-ground vegetation macrofossils (*Sphagnum* leaves and stems) extracted from peat bounding the tephra layer identified at Bagno Kusowo. Samples were submitted to Poznań Radiocarbon Laboratory, Poznań, Poland, for ^{14}C dating. Samples were pre-treated using standard acid–alkali–acid treatment and rinsed thoroughly with de-ionized water between each acid/alkali stage. All dates were calibrated using OxCal v 4.2.4 (Bronk Ramsey, 2009) and the IntCal13 atmospheric curve (Reimer *et al.*, 2013). An age model for the Linje core was developed based on ^{210}Pb and ^{14}C chronologies and is reported elsewhere (Marcisz *et al.*, 2015).

Results and tephra assignments

Linje mire

The top 70 cm of peat at Linje mire contained only one tephra layer (Linje-1, 29 shards cm^{-3}) at a depth of 59–60 cm; no tephra shards were identified elsewhere in the core. The largest shard identified in the Linje-1 tephra layer had a length of 190 μm, and median shard length was 75 μm. The major element geochemistry of glass shards from Linje-1 is rhyolitic, with a high MgO content typical of the Askja 1875 tephra (AD 1875) (e.g. Larsen *et al.*, 1999) (Fig. 2). The assignment of Linje-1 to the eruption of Askja 1875 is further supported by both the ^{210}Pb and the ^{14}C age–depth models from the same core (Marcisz *et al.*, 2015), which suggest that the age of the Linje-1 tephra is *ca.* AD 1830–1860 (Fig. 3).

Bagno Kusowo

Two tephra layers were identified in 8 m of peat at Bagno Kusowo. Glass shards were detected at a depth of 412–415 cm (Kusowo-1, peak concentration at 413–414 cm). The largest shard identified in the Kusowo-1 layer was 95 μm, and median shard length was 35 μm. The age of the tephra layer was calculated based on linear interpolation between two closely spaced radiocarbon dates to be *ca.* AD 690–850 (Table S2; Fig. 4). The analyses of major elements of glass shards from Kusowo-1 indicate geochemical similarity to glass shards from the AD 860 B tephra (AD 846–848) (Fig. 2). Given stratigraphic and geochemical constraints we correlate the Kusowo-1 to the AD 860 B tephra. One glass shard has a different major element geochemistry to most shards in Kusowo-1 and shows similarity to shards from the MOR-T4 tephra (ca. AD 1000).

A small concentration of shards (<5 shards cm^{-3}) was identified at a depth of 670–680 cm in the Kusowo core. However, due to the small shard size and low concentrations of shards, tephra from this depth was not viable for geochemical analysis.

Discussion and conclusions

Tephrostratigraphy of historical times in northern central Poland

The eruption of the Icelandic volcano, Askja, began on 28 March 1875 and had an estimated volcanic explosivity index of 5 (Carey *et al.*, 2010). Tephra was dispersed towards the east and has been identified widely in Scandinavia

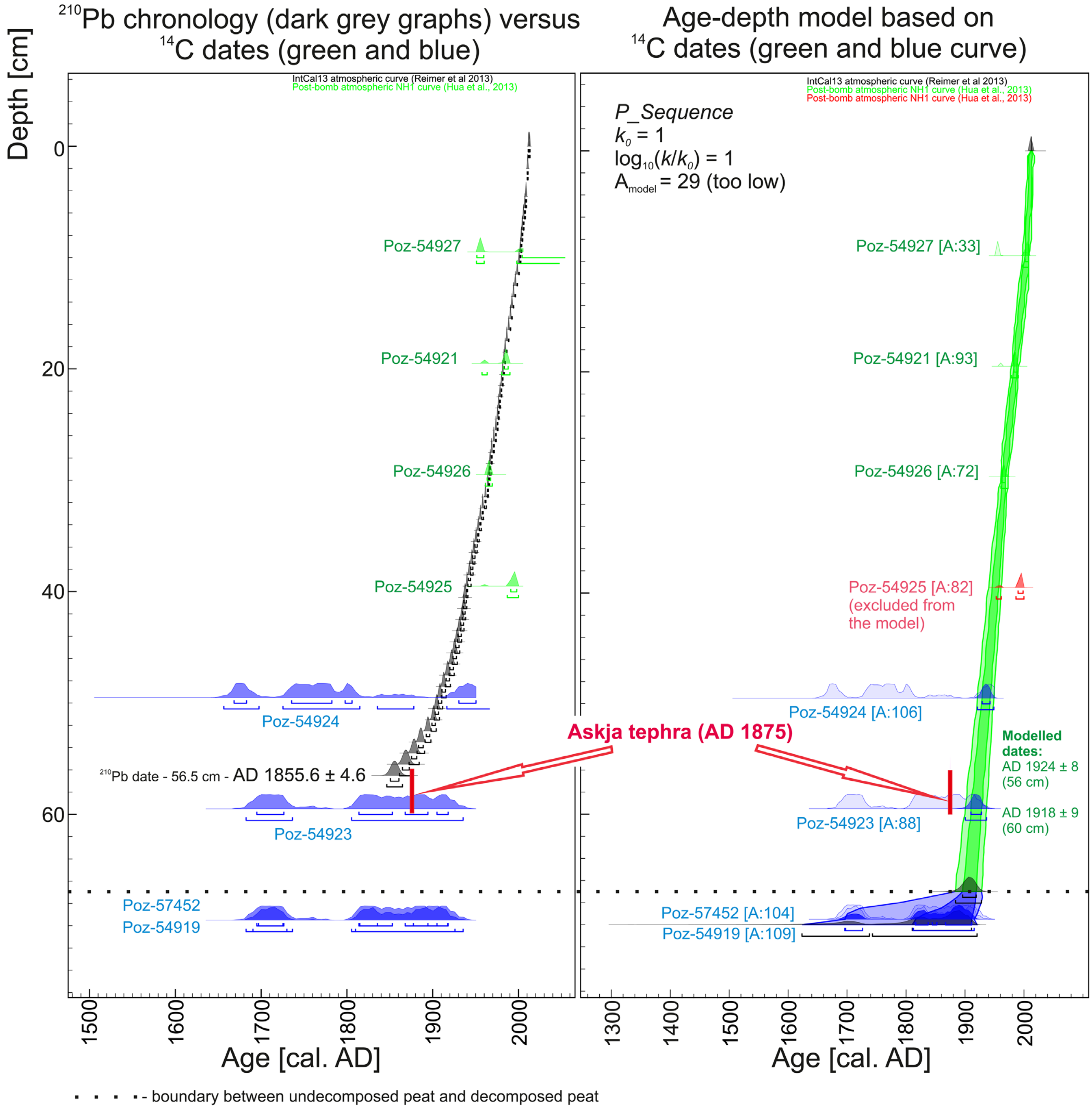

Figure 3. The Askja tephra layer versus ^{210}Pb chronology and the age–depth model based on ^{14}C dates (Marcisz *et al.*, 2015). The model was calculated using the OxCal 4.2.4 program (Bronk Ramsey, 2008, 2009).

(Wastegård, 2005), at two sites in Germany (van den Bogaard and Schmincke, 2002; Wulf *et al.*, 2016) and most recently in one peatland and two lakes in Latvia (Stivrins *et al.*, 2016). The identification of Askja 1875 in Linje mire represents the first identification of this tephra in a Polish peatland, although it was recently reported in the laminated sediments of two lakes: Lake Czechowskie, some 80 km due north of Linje (Wulf *et al.*, 2016) and Lake Żabińskie, north-east Poland (Tylmann *et al.*, 2016). We did not detect any trace of shards which might be derived from the Askja 1875 eruption in the top of the core from Kusowo peatland some 100 km due west of Lake Czechowskie.

The AD 860 B (AD 846–847: Coulter *et al.*, 2012) tephra has been identified at 20 sites in Ireland, Great Britain, Scandinavia and Germany (Pilcher *et al.*, 1995; van den Bogaard and Schmincke, 2002; Langdon and Barber, 2004). The tephra has recently been correlated to the White River Ash east (WRAe) tephra, derived from an eruption of the Churchill volcano in Alaska (Jensen *et al.*, 2014). The identification of the AD 860 B tephra at Kusowo represents the most easterly occurrence of this tephra. Tephra shards from the AD 860 B layer were transported some 7000 km across the Atlantic, before fallout onto Kusowo mire. One shard from the Kusowksie-1 tephra layer showed geochemical similarity to the MOR-T4 tephra (ca. 1000 AD) (Chambers *et al.*, 2004). The MOR-T4 tephra has not previously been recorded outside of Great Britain and Ireland. Given that only one shard was identified, we are unable to conclusively say whether the MOR-T4 tephra was deposited over Poland. However, given that this tephra is geochemically quite distinct, and fell out around the same time as AD 860 B, there is a possibility that the fallout

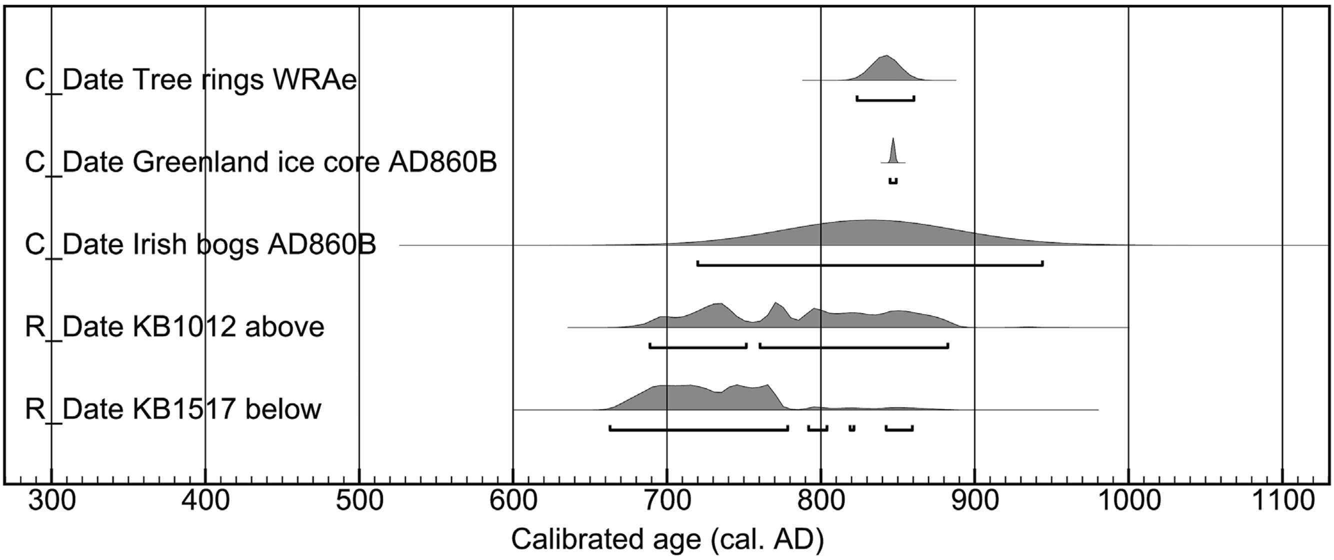

Figure 4. Ages of AD 860 B tephra from various archives across northern Europe. References: the age of the WRAe tephra is based on tree ring measurements on spruce killed by the eruption (Jensen *et al.*, 2014); the age of the AD 860 B tephra in the NGRIP ice core (Coulter *et al.*, 2012); the age of the AD 860 B tephra based on wiggle-match ^{14}C dating in Irish bogs (Pilcher *et al.*, 1995); two ^{14}C dates (KB10-12 and KB15-17) bounding the Kusowo-1 tephra from Bagno Kusowo peatland reported in this study.

range for the MOR-T4 tephra is much larger than previously thought.

Based on the depth at which the AD 860 B tephra was identified at Kusowo, the estimated age of the sparse concentration of shards between 670 and 680 cm is *ca.* AD 250. Therefore, it cannot be discounted that these shards correspond to one of the 'Unknown Icelandic tephras', two cryptotephra layers (JC09_B2_170-173_T and JC09_BC_155-158_T) of identical composition with an age of 10 BC ± 20 (varve years) and AD 60 ± 20 (varve years), which were reported in Lake Czechowskie by Wulf *et al.* (2016). However, given the extremely low concentrations of shards identified in Lake Czechowskie (2 and 6 shards cm^{-3}) fallout from these events might have been concentrated into detectable levels in some areas of the lake basin, but might be below detection levels in Polish peatlands (Watson *et al.*, 2016).

Tephra shard size

The discovery of shards of 190 and 95 μm in length at fallout sites ~2500 and 7000 km from their volcanic sources indicates the potential for the long-distance transport of relatively large volcanic ash particles. The median shard size for the Askja 1875 tephra at Linje (75 μm) suggests that this tephra was not at the end of its range, and shards of an analysable size may well have been transported further east and south-east to sites in Belarus or the Ukraine.

Conclusions

The discovery of tephra from both Iceland and Alaska in Polish peatlands indicates the potential for the discovery of more tephra layers in Poland. The discovery of Askja 1875 in a Polish peatland underlines the importance of this tephra layer as a chronological marker in Eastern Europe. The large size of the shards identified in the Askja 1875 tephra layer at Linje indicates that shards from this tephra might still be of a geochemically analysable size in sites further east. We record the most easterly reported occurrence of the AD 860 B tephra some 7000 km from its origin in Alaska. The AD 860 B tephra was not identified in the sediments at Lake Czechowskie (100 km due east of Kusowo). The tephra layers we identify have been identified at other sites in north and west Europe and offer the opportunity to synchronize and compare palaeoenvironmental records across Europe, from the oceanic climates of Western Europe to the more continental regions of Eastern Europe. However, the patchy distribution of tephra necessitates the examination of more sites in Eastern Europe before a regional tephrostratigraphy can be established.

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Supplementary information

Table S1. Raw EPMA data for Kusowo-1 and Linje-1.
Table S2. Radiocarbon dates obtained on samples from Kusowo Bagno peatland.

Abbreviations. EPMA, electron probe micro analysis.

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